

Current Status of the High-Efficiency L-band Transmit/Receive Module Development for SAR Systems

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Abstract --Large, lightweight, high power, L-band phased-arrays are required to enable future NASA synthetic aperture radar (SAR) missions. The transmit/receive (T/R) module is a key component in SAR antennas and the T/R module efficiency has direct implications on the power dissipation and power generation requirements of the system. Significant improvements in the efficiency of the T/R module will make SAR missions more feasible and affordable. The efforts described in this paper are part of a three-year on-going task sponsored by the NASA Earth Science Technology Office (ESTO) under the Advanced Component Technology (ACT) program. We will describe the current status and recent results of a novel T/R module technology to achieve ultra-high efficiencies. The T/R module performance goal is to achieve an overall module efficiency greater than 70% with a minimum of 30-Watts output power at L-band frequencies.

I. INTRODUCTION

Radar remote sensing plays an important role in deriving unique measurements that address fundamental questions in the National Aeronautic and Space Administration (NASA) Earth Science Enterprise (ESE) strategic plan [1]. Synthetic aperture radar (SAR) can provide measurements key to the water cycle (e.g. soil moisture and water level), global ecosystem (biomass estimation, land cover change), and ocean circulation and ice motion. L-band repeat-pass interferometric SAR (InSAR) techniques can provide very accurate and systematic measurements of surface deformation and surface strain accumulation due to seismic and volcanic activity [2]. L-band InSAR is also useful for natural hazard monitoring, assessment and disaster response. L-band radar provides the ability to make these measurements under a variety of topographic and land cover conditions, day or night, with wide coverage at fine resolution and with minimal temporal decorrelation [3,4].

A. Project Description

Future NASA SAR missions require high power radar antennas. The antenna must also be large, lightweight and

electronically steered [5,6]. The transmit/receive (T/R) module is a key component of SAR antennas. Significant improvements in T/R module efficiency will reduce overall power consumption, simplify the thermal design and increase reliability. By miniaturizing the T/R modules, they can be used for both conventional rigid panel phased-array antennas as well as in more advanced super lightweight flexible membrane antennas currently being developed for future NASA missions.

In this research, a new high-efficiency T/R module is being developed because conventional T/R modules will not meet the performance and cost goals. We are investigating the use of L-band Class-E/F power amplifiers for use in the new high-efficiency T/R module. The objectives of this work are to extend the operating frequency of Class-E/F power amplifiers to L-band and then demonstrate their utility as an integral component of the radar T/R module. Finally, we will miniaturize the module to be compatible with large, lightweight antennas. The performance goals of the T/R module, given in Table I, are to achieve 30 Watts output power at L-band (1.25 GHz) with greater than 80 MHz bandwidth and over 70% transmitter efficiency. Current T/R modules can only achieve moderate efficiencies of 30-40%.

TABLE I
PERFORMANCE GOALS OF THE INTEGRATED T/R MODULE

Parameter	Value
Frequency	1250 MHz
Bandwidth	80 MHz
Peak Transmit Power	30 Watts
Overall Module Efficiency	70%
Pulsewidth	50 μ sec
PRF	2000 Hz
Transmit Gain	48 dB
Receive Gain	25 dB
Receive Noise Figure	< 2.5 dB
Phase Shifter	6-bit
Rx Third Order Intercept (output)	> +5 dBm
Tx/Rx Programmable Attenuator	30 dB in 0.5 dB steps
T/R Module Mass	<100 g
T/R Module Size	2.5in x 1.5in x 0.25in

II. CLASS-E/F POWER AMPLIFIERS

At the heart of the T/R module is a high-efficiency switching power amplifier (PA). Switching amplifiers, such as Class-E and the recently reported Class-E/F amplifiers [7,8], use the active devices as switches. That is, the active device is ideally fully-on (short-circuit) or fully-off (open-circuit). When the switch is turned on, the transistor is modeled by a small on-resistance, and when the switch is turned off, the transistor is modeled by the transistor's output capacitance. These circuits are commonly found in switching power supplies, but only recently have they been exploited as RF amplifiers due to the availability of transistors with substantial gain and power at microwave frequencies. The theoretical efficiency for Class-E and Class-E/F amplifiers is 100%; practical efficiencies of 70-90% have been demonstrated at VHF and UHF frequencies. A 50 MHz high-efficiency (93%) high power (30W) Class-E power amplifier [9] and a 144MHz Class-E amplifier with 54W output power and 70% efficiency [10] were recently reported. Feasibility of operating Class-E amplifiers at microwave frequencies was demonstrated with a 1W amplifier at 1.9GHz with 41% efficiency [11].

A. Push-Pull Class-E/F Circuit Topology

For this development we have selected the Class-E/F circuit topology. Fig. 1 shows the schematic of a Class-E/F amplifier in push-pull configuration. The amplifier uses a pair of transistors as switches. It incorporates two baluns to make single-ended to differential-ended conversion. At the output of the amplifier, the inductance of the balun and the output capacitance of the transistor are tuned to form a parallel resonance LC tank at the operating frequency of the amplifier.

The push-pull Class-E/F amplifier has several advantages over a Class-E amplifier. It combines two transistors to achieve higher power level. It incorporates the transistor output capacitance into the tuning circuit. Since most high power devices have high output capacitance, this feature improves the performance of the tuning circuit and allows high operating frequency. By symmetry of the push-pull configuration, the amplifier suppresses the even harmonics of the operating frequency, thereby achieving higher efficiency. The Class-E/F amplifier also has lower peak voltage and lower RMS current, which reduces resistive loss of the circuit. Lower peak voltage is desired because the transistor can have a lower breakdown voltage. Lower RMS current reduces the power dissipated. It has soft-switching, which keeps the current at a low level while the capacitors discharge. This feature reduces the discharging loss of the amplifier. The Class-E/F amplifier also has a less complex circuit for lower production cost and higher reliability.

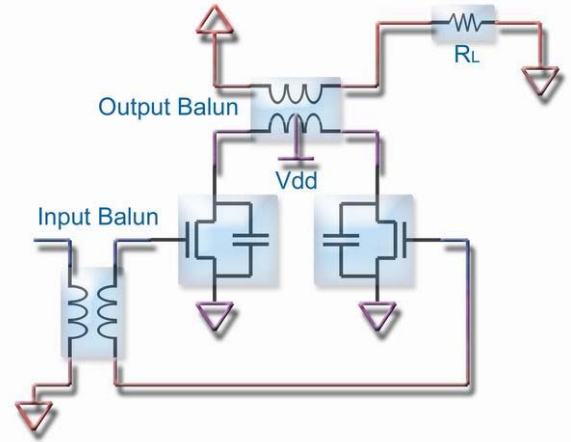


Fig. 1. Schematic of Push-Pull Class-E/F Power Amplifier

B. Low loss L-band microstrip balun

Due to the topology of push-pull amplifiers, a balun is required at the input and output of the amplifier to make single-ended to double-ended conversions. There are many different varieties of microwave baluns. However, at L-band, the traditional microwave baluns are not practical due to the large size. An interdigital microstrip balun is being developed for the amplifier. This balun is smaller than a conventional microwave balun. It is low loss, planar and easy to manufacture. Using interdigital coupled inductors (Fig. 2), the magnetic field is more confined inside the structure, which increases the magnetic coupling between the primary and the secondary inductors.

We have designed an interdigital balun using the coupled microstrip inductors. Each microstrip line is broken into several narrower lines. They are placed alternately as shown in the figure. Bond wires or short metal strips are used to connect the ends of the microstrip lines. The magnetic field is better confined in this configuration, while the inductance does not change. Therefore, a better coupling coefficient is achieved. The improved coupling provides optimal output load impedance, thereby improving the efficiency. Also, the bandwidth is improved by the higher coupling coefficient.

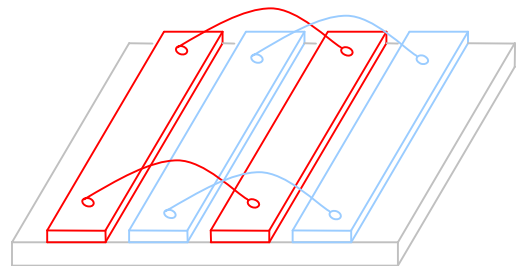


Fig. 2. Interdigital coupled inductors.

III. L-BAND HIGH EFFICIENCY T/R MODULE

To demonstrate the Class-E/F amplifier as an integral component of the radar T/R module, a complete L-band T/R module is being designed and built. A key component in the module is the 30W high-efficiency Class-E/F power amplifier. The goal is to achieve the highest possible efficiency in both the transmit and receive modes. The module contains a complete 30W transmitter, a low noise amplifier and a common 6-bit programmable attenuator and phase shifter.

A. Design

The block diagram of the T/R module, given in Fig. 3, shows all of the elements of the transmitter, receiver and the control and power switches. The transmit chain consists of a 3W driver amplifier which drives the Class-E/F power amplifier. The RF circuits use GaAs MMICs except for the high-efficiency power amplifier which currently uses silicon LD-MOS technology. A more detailed description of the T/R module design and performance analysis is provided in [12].

To achieve an overall module efficiency of 70%, the 30W power amplifier requires an 80% drain efficiency. To ensure

the receiver does not contribute significantly to overall module efficiency, the receive chain will use less than 100 mW of DC power. For the current design, the calculated DC power (at 10% duty cycle) is 4.2W which corresponds to 67% overall module efficiency. We believe that with further improvements in other components of the module (i.e. driver amplifier and circulator), and overall efficiency of 70% is achievable.

B. Implementation

A preliminary layout of the T/R module is shown in Fig. 4. The circuits will be integrated on one multi-layer circuit board to achieve a compact T/R module package. The module size is estimated at 2.5in x 1.5in x 0.25in and the weight is less than 100 grams. All of the components are surface mount devices and will be eutectically attached to the printed circuit board except for the power amplifiers and the circulator. These will be soldered directly to the plated aluminum baseplate for good grounding and heat sinking. A matching network between the driver and the high power amplifier will be incorporated to optimize the VSWR and efficiency.

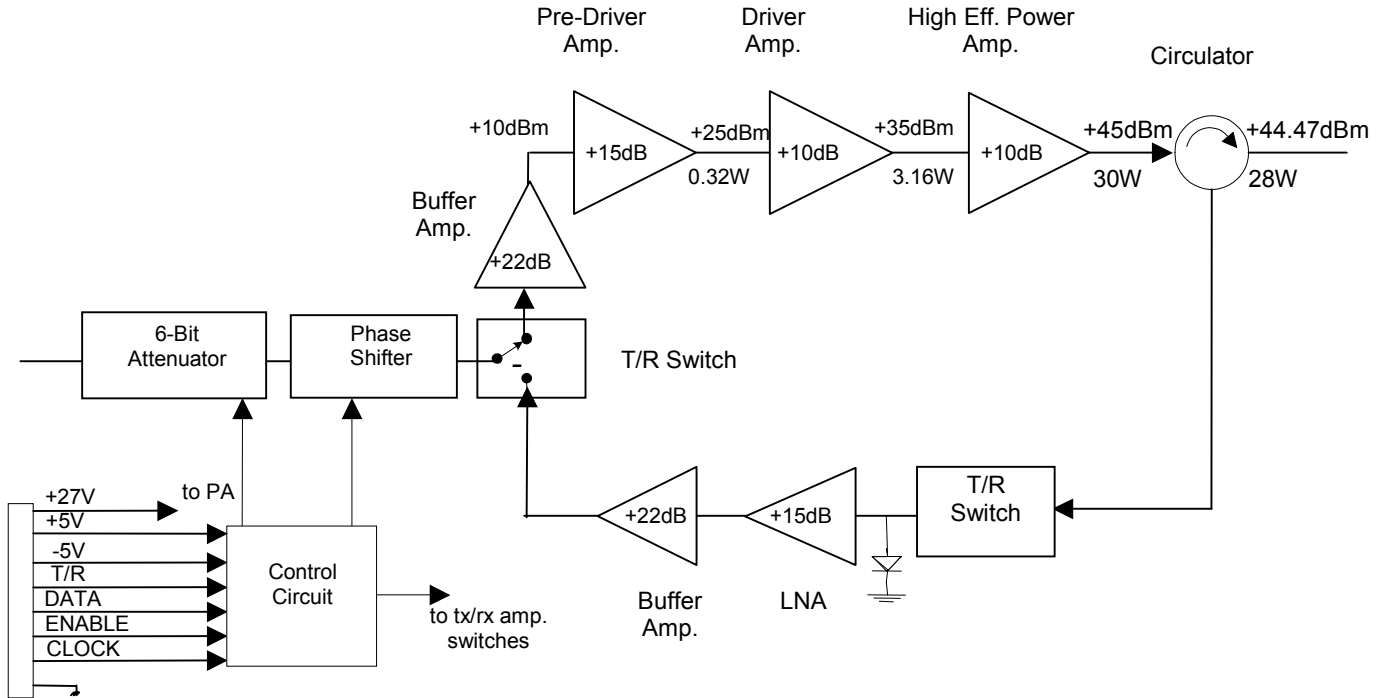


Fig. 3. L-band T/R Module block diagram. The 30W Class-E/F power amplifier is the final power amplifier.

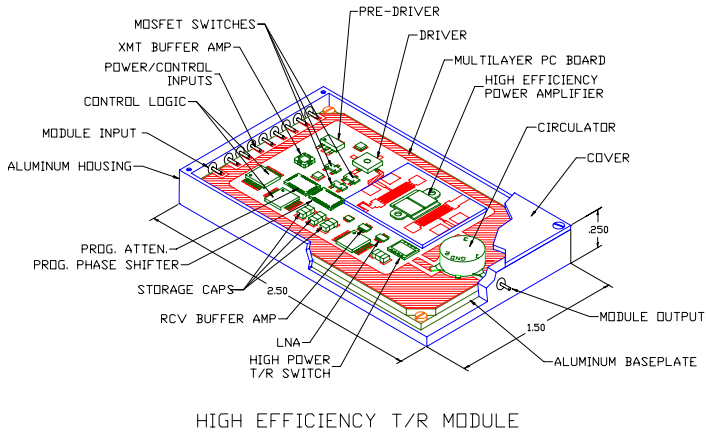


Fig. 4. Preliminary layout of integrated T/R module.

IV. STATUS AND RESULTS

The results reported here are of the first phase of the program to establish overall feasibility of using Class-E/F amplifiers at microwave frequencies and to establish their utility as an integral element of a new T/R module architecture that can achieve very high operating efficiencies.

Several iterations of the Class-E/F power amplifier were built and tested. Fig. 5 shows a picture of one of the PA prototypes. For this amplifier, the output power and drain efficiency were measured and shown in Fig. 6. The measurement was performed at 900 MHz. At 30 W output

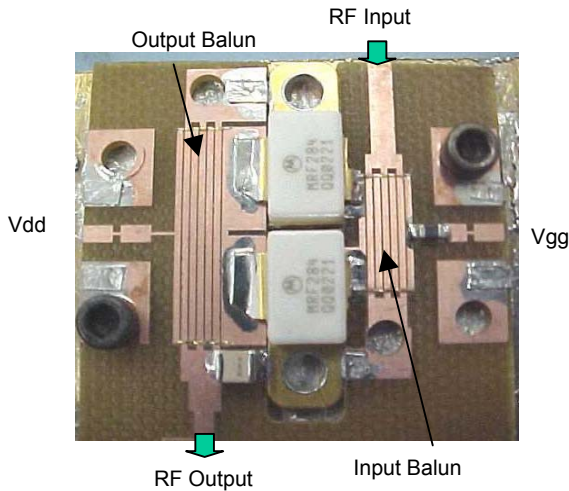


Fig. 5. Picture of L-Band Class E/F PA

power level, 12 dB gain and 64% drain efficiency was achieved. The current operating frequency is less than the target 1215-1300 GHz, which is believed to be caused from errors in the balun and matching circuit models at high frequencies. To better understand the problem, circuit models of the balun and matching circuits were improved and validated using both HFSS and Sonnet electromagnetic simulators to better correlate with measurement results.

To improve performance and efficiency of the amplifier, the AC ground and the heat sink have been improved, pushing up the efficiency from 64% to 73%. Bias networks were also modified to eliminate an undesired low-frequency transistor gate oscillation. We are continuing to improve the balun to achieve better balance and higher coupling coefficient. Better balance can be achieved by reducing the size of the balun. Higher coupling coefficient can be achieved by using multilayered circuit board.

In parallel with the Class-E/F PA development, a breadboard 3-Watt T/R module (excluding the 30W PA) was built using commercially available components (Fig. 7). Each T/R component has been individually tested and characterized in ambient environment. All measured results agree with prediction and are within specification. End-to-end performance testing of the 3-W T/R module is in progress and will be completed prior to integration with the 30-W Class-E/F power amplifier.

Once the 30-W PA is operating at the required L-band frequency, it will be integrated with the T/R module to verify overall performance before proceeding to the next phase.

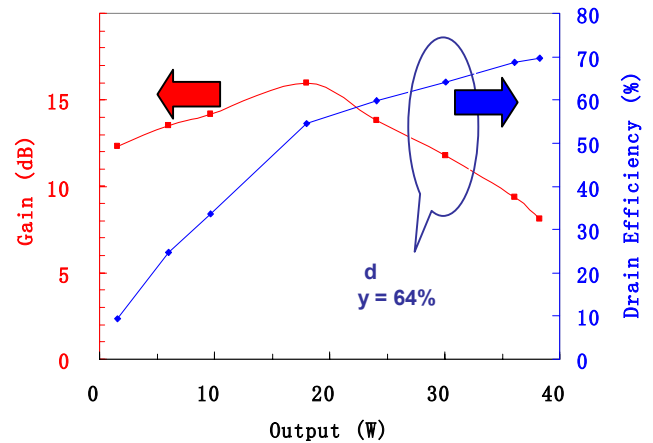


Fig. 6. Output power, efficiency and gain of the PA at 900 MHz

V. FUTURE WORK

Improvements to the power amplifier performance are being addressed. Currently the amplifier works at 900 MHz, which differs from the target frequency of operation. The first step is to adjust the center frequency of the amplifier to 1.25 GHz as already discussed. To further improve the efficiency of the amplifier, harmonic traps will be added at the output to reduce the harmonics of the fundamental frequency and to prevent the undesired harmonics from delivering to the load. Once we optimize the performance of the PA and address any interface issues, the entire T/R module will be integrated on a multilayer circuit board for a compact T/R module package. The miniaturized module will under go ambient and limited environmental testing to raise the TRL to 5.

A key challenge has been finding a high power device with low drain capacitance and low on-resistance which is necessary to push up the frequency. GaAs FET devices are a possible alternative. Also wide bandgap devices, such as SiC and GaN transistors, have shown promise in high-frequency and high-power applications. The comparison between LDMOS, GaAs, SiC and GaN, will be a part of future studies.

VI. SUMMARY

A Class-E/F power amplifier based on LD-MOS transistors operating at 900 MHz was demonstrated experimentally. The 30-Watt amplifier achieved 73% efficiency. Efforts are underway to increase the operating frequency to L-band (1250 MHz) and improve the efficiency by improving the balun circuit. A complete L-band T/R module has been designed, simulated and prototyped which will incorporate the Class-E/F amplifier. Performance predictions indicate a 67% overall module efficiency is achievable.

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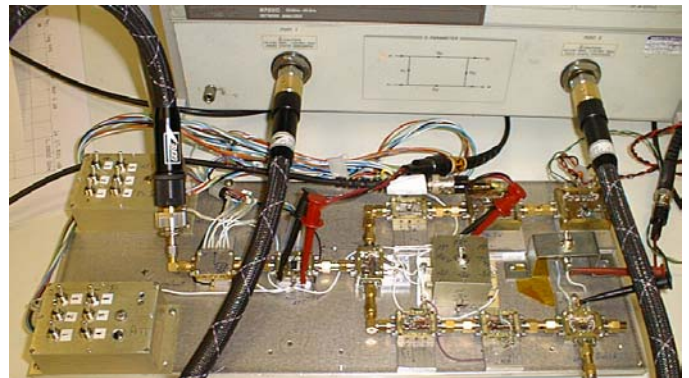


Fig. 7. Breadboard testing of the 3W L-band T/R module. The Class-E/F amplifier has not yet been integrated.

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